DP IB Environmental Systems & Societies (ESS): HL

Your notes

2.3 Biogeochemical Cycles

Contents

Biogeochemical Cycles

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Introduction to Biogeochemical Cycles

- Biogeochemical cycles are natural processes that **circulate** the **chemical elements** necessary for **life**
  - They include cycles such as:
    - The carbon cycle
    - The nitrogen cycle
    - The hydrological cycle
  - These cycles ensure that these elements continue to be **available** to living organisms
  - This means they play a very important role in maintaining the balance of ecosystems and supporting life on Earth

Human impact

- Human activities such as burning fossil fuels, deforestation, urbanisation and agriculture can **disrupt** biogeochemical cycles
  - This can lead to environmental **imbalances** and threaten the **sustainability** of ecosystems
    - For example, deforestation can disrupt the carbon cycle by reducing the number of trees available to absorb carbon dioxide from the atmosphere

Components of biogeochemical cycles

- Biogeochemical cycles are made up of:
  - Stores
  - Sinks
  - Sources

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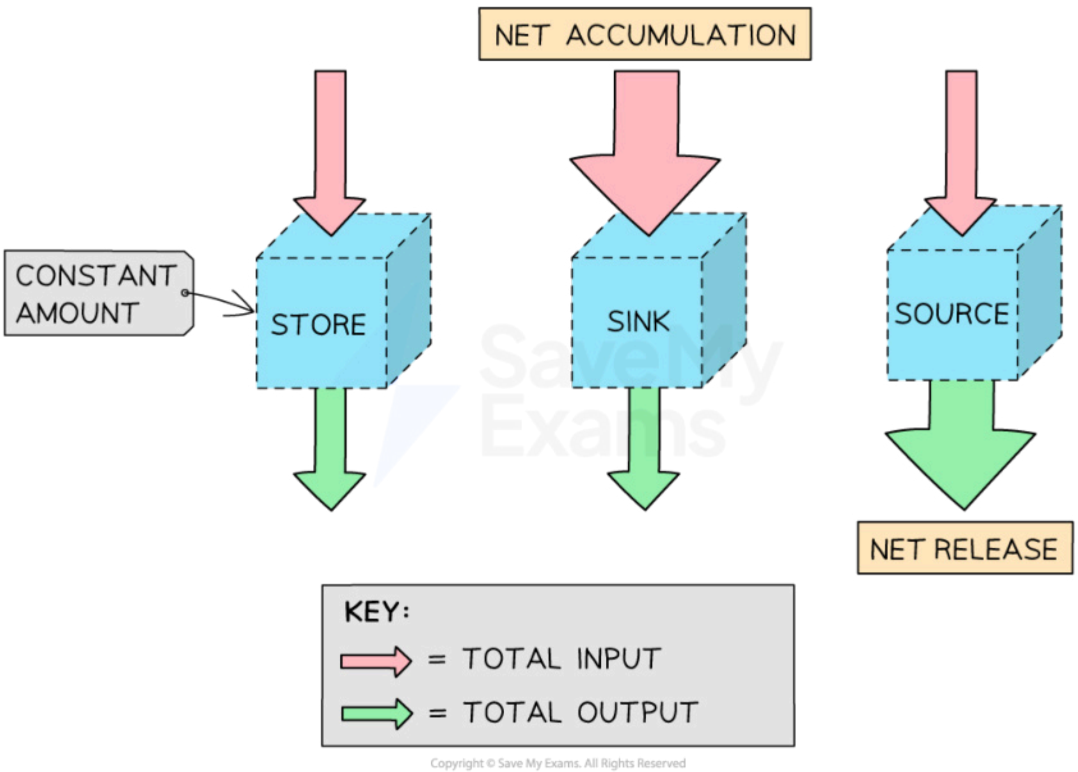

Stores, Sinks & Sources

A component in a biogeochemical cycle can be described as a store, sink or source depending on the size of its net input relative to its net output

- **Stores**:
  - Also known as **storages**
  - They are "reservoirs" where elements are held for varying periods of time
  - They represent areas where the element remains in **equilibrium** with the environment i.e. the **total input** of the element is **equal** to the **total output**
  - Examples include oceans, atmosphere, soil and living organisms
    - For example, the ocean serves as a major store of carbon in the carbon cycle, with dissolved carbon dioxide being absorbed by seawater
    - At the same time, an equivalent amount of carbon dioxide is released back into the atmosphere, maintaining equilibrium
  - They can either be **natural** or **artificial**

- **Sinks**:
  - Sinks represent parts of the cycle where a particular element **accumulates** over time
  - They are areas where the **total input** of the element is **greater than** the **total output**
    - This results in the **net accumulation** of the element
    - For example, fossil fuel deposits act as sinks for carbon in the carbon cycle, storing carbon that was once part of living organisms
  - They can either be **natural** or **artificial**
- **Sources**:
  - Sources **release** elements into the cycle
  - They represent parts of the cycle where the **total output** of the element is **greater than** the **total input**
    - This results in **net release** of the element
    - For example, volcanic eruptions release large amounts of carbon dioxide into the atmosphere, acting as a source in the carbon cycle
  - They can either be **natural** or **artificial**

Your notes

Carbon Cycle

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Carbon Cycle

- Many different **materials** cycle through the abiotic and biotic components of an ecosystem
  - All materials in the living world are **recycled** to provide the building blocks for future organisms
- Elements such as **carbon** are **not limitless** resources
  - There is a finite amount of each element on the planet
  - Elements need to be recycled in order to allow new organisms to be made and grow
- Carbon is constantly being recycled around the **biosphere** so that the total amount of carbon in the biosphere is essentially **constant**
  - Carbon is transferred from one form to another by the various processes in the carbon cycle

Organic and inorganic carbon stores

- Organisms, crude oil and natural gas contain organic stores of carbon
  - Organic stores refer to the carbon-containing compounds found in organisms and fossil fuels
  - For example, carbon in these stores may exist as carbohydrates in organisms or hydrocarbons in fossil fuels
- Inorganic stores exist in the atmosphere, soils and oceans
  - Inorganic stores refer to reservoirs of carbon that exist in other non-living components of the biosphere
  - For example, carbon in these stores may exist as carbon dioxide or carbonates

Equilibrium and residence time

- A carbon store is in **equilibrium** when absorption (uptake) is **balanced** by the release
  - For example, the carbon stored in trees through photosynthesis is balanced by the carbon released during respiration
- **Residence time** is the average time that a carbon atom **remains** in a **store**
  - Without human interference like mining, the residence time in fossil fuels would be measured in hundreds of millions of years

Carbon flows in ecosystems

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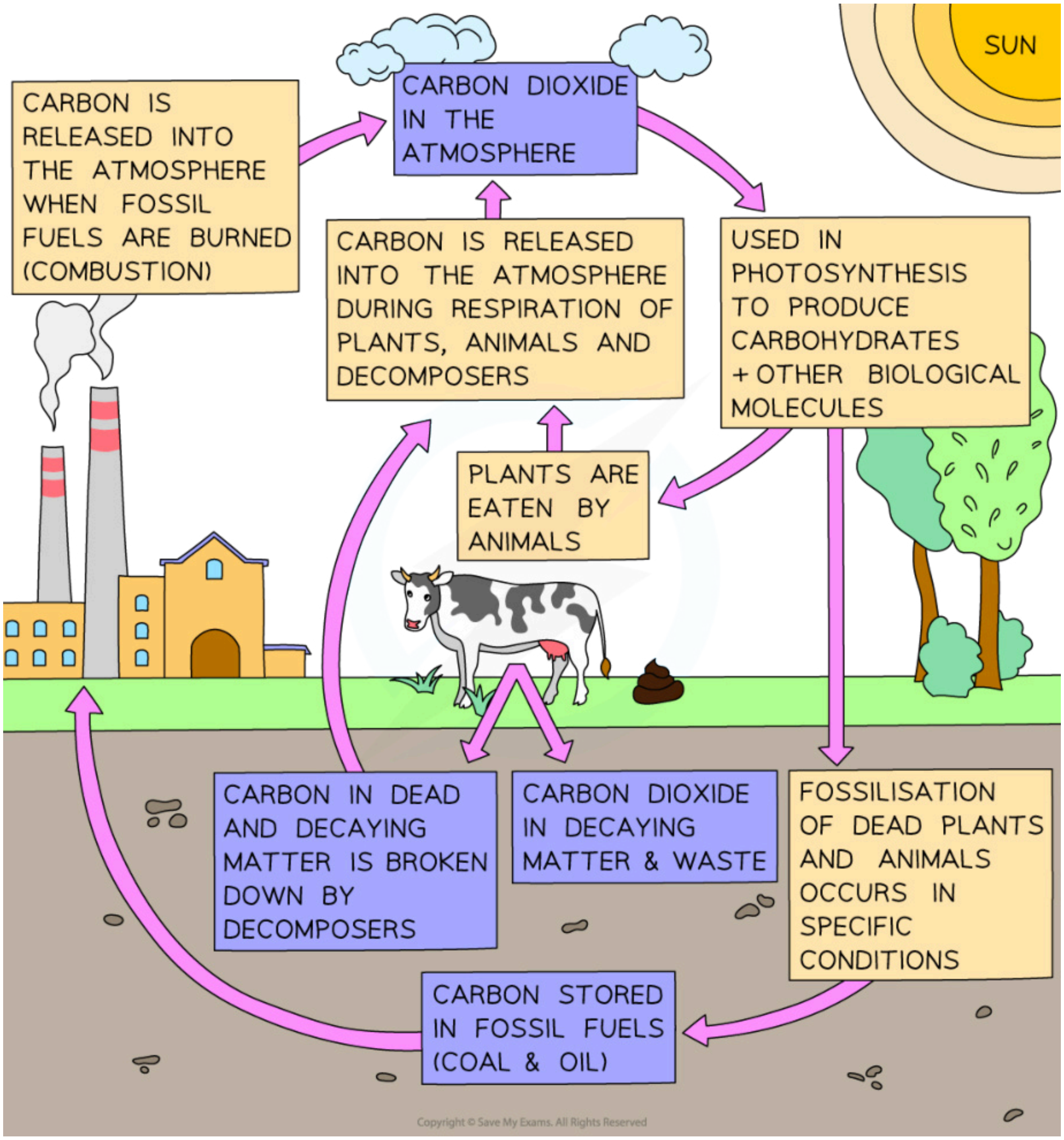
- Carbon flows between stores in ecosystems through various processes
- The main processes include:
  - **Photosynthesis** (transformation)—plants absorb CO_2 and convert it into organic compounds (carbohydrates)
  - **Cellular respiration** (transformation)—both plants and animals release CO_2 during respiration
  - **Feeding** (transfer)—animals consume organic matter, transferring carbon through the food chain
  - **Defecation** (transfer)—carbon is returned to the soil through waste products
  - **Death** and **decomposition** (transfer)—decomposers break down dead organisms, releasing carbon back into the soil
- Other processes include:
  - **Fossilisation**—if animals and plants die in conditions where decomposing microorganisms are not present, the carbon in their bodies can be converted, over millions of years and significant pressure, into fossil fuels such as **peat** and **coal**
    - Aquatic organisms that die also form sediments on the sea bed

      These can go on to form other fossil fuels like **oil** and **gas**
  - **Combustion**—when fossil fuels are **burned**, the carbon locked within them combines with oxygen to form CO_2, which is released into the atmosphere



The carbon cycle

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Carbon sequestration

- Carbon sequestration is the process of **capturing atmospheric CO_2** and **storing** it in solid or liquid forms

- For example, trees naturally sequester carbon by absorbing CO_2 during photosynthesis and storing it in their biomass
- Organic matter can be fossilised over millions of years to form coal, oil and natural gas, resulting in carbon being stored underground

Ecosystems as stores, sinks or sources

- Ecosystems can act as stores, sinks or sources of carbon depending on the **balance** between **inputs** and **outputs**
- Net accumulation of carbon or net release of carbon is determined by the difference between total inputs and outputs
- For example:
  - Young forest ecosystem: acts as a sink, as photosynthesis exceeds respiration, leading to net uptake of CO_2
  - Mature forest ecosystem: acts as a store, with carbon cycling between living organisms, soil and atmosphere
  - Forest destruction (fire or deforestation): acts as a source, releasing stored carbon back into the atmosphere

Examiner Tips and Tricks

Don't be overwhelmed by the carbon cycle—it's actually quite simple:

- Carbon is taken out of the atmosphere by photosynthesis
- It is passed on to animals and decomposers by feeding
- It is returned to the atmosphere by respiration; in plants, in animals and in decomposing microorganisms
- In addition, it is returned by combustion of fossil fuels

Make sure you are able to identify what each arrow represents in any diagram of the carbon cycle.

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Human Impacts on the Carbon Cycle

Fossil fuels

- Fossil fuels like coal, oil and natural gas are stores of carbon with virtually unlimited residence times
- Fossil fuels were formed when past ecosystems acted as **carbon sinks**, trapping organic carbon over millions of years
  - They were created from ancient plants and animals that lived millions of years ago
  - Over time, their remains got buried deep underground
  - As they were buried, pressure and heat turned them into fossil fuels
- Humans burn fossil fuels for energy production
  - When burned, these fuels release heat energy
  - The heat energy can be harnessed to generate electricity, power vehicles, heat buildings and fuel industrial processes
- When burned, fossil fuels become **carbon sources**, releasing stored carbon back into the atmosphere as carbon dioxide

Agricultural systems

- Agricultural systems can act as carbon sinks or carbon sources depending on the type of agricultural and the management techniques used:
  - **Carbon sinks**: regenerative agriculture techniques like crop rotation, cover cropping, and no-till farming result in soil acting as a carbon sink
    - This is because these methods **increase** the amount of **organic matter** in the soil
  - **Carbon sources**: drainage of wetlands, monoculture farming and intensive tillage result in soil acting as a carbon source
    - This is because these methods increase the **release** of carbon from soils
- Longer-term cropping practices, such as timber production, also affect carbon cycling and storage in ecosystems
  - When forests are managed sustainably for timber production, they can act as significant carbon sinks

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    - This is because they **sequester** carbon dioxide from the atmosphere through photosynthesis and **store** it in woody biomass and soil organic matter
  - However, if forests are clear-cut or managed unsustainably, they can become carbon sources
    - This is because stored carbon is **released** back into the atmosphere (when the harvested wood is burned) **quicker than it is stored** in new tree growth

Oceanic carbon dynamics

- Carbon dioxide is absorbed into oceans by **dissolving in sea water**
  - It can also **come out of the solution** and is released as a gas when conditions change (e.g. when ocean temperature increases)
- Normally, oceans act as a significant carbon sink, absorbing CO_2 from the atmosphere and helping to regulate atmospheric carbon levels
  - However, the burning of fossil fuels by humans is releasing CO_2 at a **faster rate than oceans can absorb**
    - This is leading to rising CO_2 levels in the atmosphere
  - In addition to warming ocean temperatures caused by human-induced climate change, this is reducing the ability of oceans to act as carbon sinks

Ocean acidification

- Increased concentrations of dissolved CO_2 in oceans **lowers the pH** of the sea water, leading to ocean acidification
- This is causing threats to marine organisms:
  - Small decreases in ocean pH reduce calcium carbonate deposition in mollusc shells and coral skeletons
  - This can lead to weakened shells, increased vulnerability to predators and smaller and less diverse reef structures

Examiner Tips and Tricks

What you need to understand here is that human activities can cause particular ecological systems (such as underground fossil fuel reserves, agricultural systems or our oceans) to act as carbon sinks/stores or as carbon sources. For example, until the industrial revolution, fossil fuels have acted as a significant carbon store but we have reversed this and have turned them into a carbon source.

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Reducing Human Impacts on the Carbon Cycle

- Human activities have **significantly altered** the carbon cycle
  - This has led to increased **atmospheric carbon dioxide** levels and **climate change**
- Measures are urgently needed to reduce these impacts and restore balance to the carbon cycle
  - Example of these measure include:

1. **Low-carbon technologies**:
   - Adopting low-carbon technologies is important for reducing carbon emissions from energy production, transportation, industry and buildings (heating, cooling etc.)
     - Examples include renewable energy sources like solar, wind and hydropower, as well as more energy-efficient technologies and practices (e.g. better insulation and heatpumps)
2. **Reduction in fossil-fuel burning**:
   - Decreasing the burning of fossil fuels is an essential step in reducing carbon emissions
     - Transitioning to cleaner energy sources, such as renewables can help achieve this
3. **Using biomass as a fuel source**:
   - Promoting sustainable cultivation of bioenergy crops that does not cause deforestation—bioenergy crops absorb carbon dioxide from the atmosphere as they photosynthesise
   - Utilising bioenergy with carbon capture and storage (BECCS) technology
     - This involves producing energy from biomass
     - The carbon dioxide emissions from biomass combustion are also captured and stored underground
     - Together these processes effectively remove carbon dioxide from the atmosphere
4. **Reduction in soil disruption**:
   - Decreasing soil disruption through sustainable agricultural practices is vital for preserving soil health and maintaining the ability of soils to sequester carbon
     - Practices such as crop rotation and cover cropping can minimise soil disturbance, erosion and loss of organic matter

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- Healthy soils with high organic carbon content act as carbon sinks, storing carbon and mitigating greenhouse gas emissions

5. **Reduction in deforestation**:
   - Implementing programs like the UN Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UNREDD)
     - This prevents deforestation and promotes sustainable forest management
6. **Carbon capture through reforestation**:
   - Reforestation involves planting trees on deforested or degraded lands to sequester carbon from the atmosphere
     - Trees absorb CO_2 during photosynthesis, storing carbon in their biomass and surrounding soils
     - Forests act as important carbon sinks
7. **Artificial sequestration**:
   - Artificial sequestration technologies capture CO_2 emissions from industrial processes and power plants, preventing them from entering the atmosphere
     - Methods include carbon capture and storage (CCS), where CO_2 is captured, transported and injected underground for long-term storage
8. **Enhancing carbon dioxide absorption by the oceans**:
   - Ocean fertilisation techniques involve adding compounds like nitrogen, phosphorus and iron to stimulate the growth of phytoplankton
     - These phytoplankton then absorb carbon dioxide through photosynthesis
   - Using methods to increase ocean upwellings
     - These upwellings bring nutrient-rich deep waters to the surface
     - This has the same effect of promoting the growth of phytoplankton and enhancing carbon dioxide absorption

Carbon Stores (HL)

Your notes

Carbon Stores

Lithosphere carbon stores

- The **lithosphere** contains significant carbon stores in **fossil fuels** and **carbonate rocks**
  - **Fossil fuels**: carbon stored in coal, oil, and natural gas
  - **Limestone**: carbon is stored as **calcium carbonate** ($CaCO_3$) in certain rocks, e.g. limestone
    - **Residence time**: carbon in these stores can remain for **hundreds of millions of years**

Formation of fossil fuels

- Fossil fuels are formed from **partially decomposed organic matter**
- **Coal**: mainly formed from dead plant material (trees and ferns) in swampy areas. This process peaked during the Carboniferous period (around 300 million years ago)
- **Oil and natural gas**: mainly formed from **marine microorganisms** like plankton
  - When they died, their bodies settled on the seafloor
  - Over time, they were buried and fossilised in **porous rocks**
- These processes took **tens of millions of years** to accumulate significant carbon stores

Biological carbon stores

Reef-building corals and molluscs

- The **hard parts** of organisms such as reef-building corals and molluscs (e.g. clams and snails) contain **calcium carbonate**
  - Calcium carbonate can become **fossilised in limestone**
  - The **largest carbon store** in Earth's systems is limestone
  - Both **biological** and **non-biological** processes can produce limestone

Methane

- Methane (**CH_4**) is a store of carbon because it contains one carbon atom bonded to four hydrogen atoms

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    - When methane is produced from **organic matter** in **anaerobic conditions** (when very little or no oxygen is available), carbon from that organic material is stored in the methane molecule
- Methane production (**methanogenesis**):
    - **Methanogenic bacteria** produce methane in anaerobic conditions
    - Anaerobic conditions occur in places like **swamps**, **rice paddies**, **landfills**, and in the **stomachs of cattle** (ruminants)
        - Swamps and wetlands are **major natural sources** of methane because of the presence of large amounts of organic material and anaerobic conditions
- Methane as a **greenhouse gas**:
    - Methane is a **potent** greenhouse gas
        - It has a global warming potential that is about 25 times higher than carbon dioxide over a 100-year period
    - It has a **residence time** of about **10 years**
        - It takes about 10 years for atmospheric methane to oxidise to **carbon dioxide**

Examiner Tips and Tricks

Not all limestone is formed by fossilisation of animal remains (e.g. coral skeletons or mollusc shells); it can also be formed by a few other **biological** and **non-biological** processes. However, details of these processes are not required for your exams. Just make sure you know the example given in this revision note!

Nitrogen Cycle (HL)

Your notes

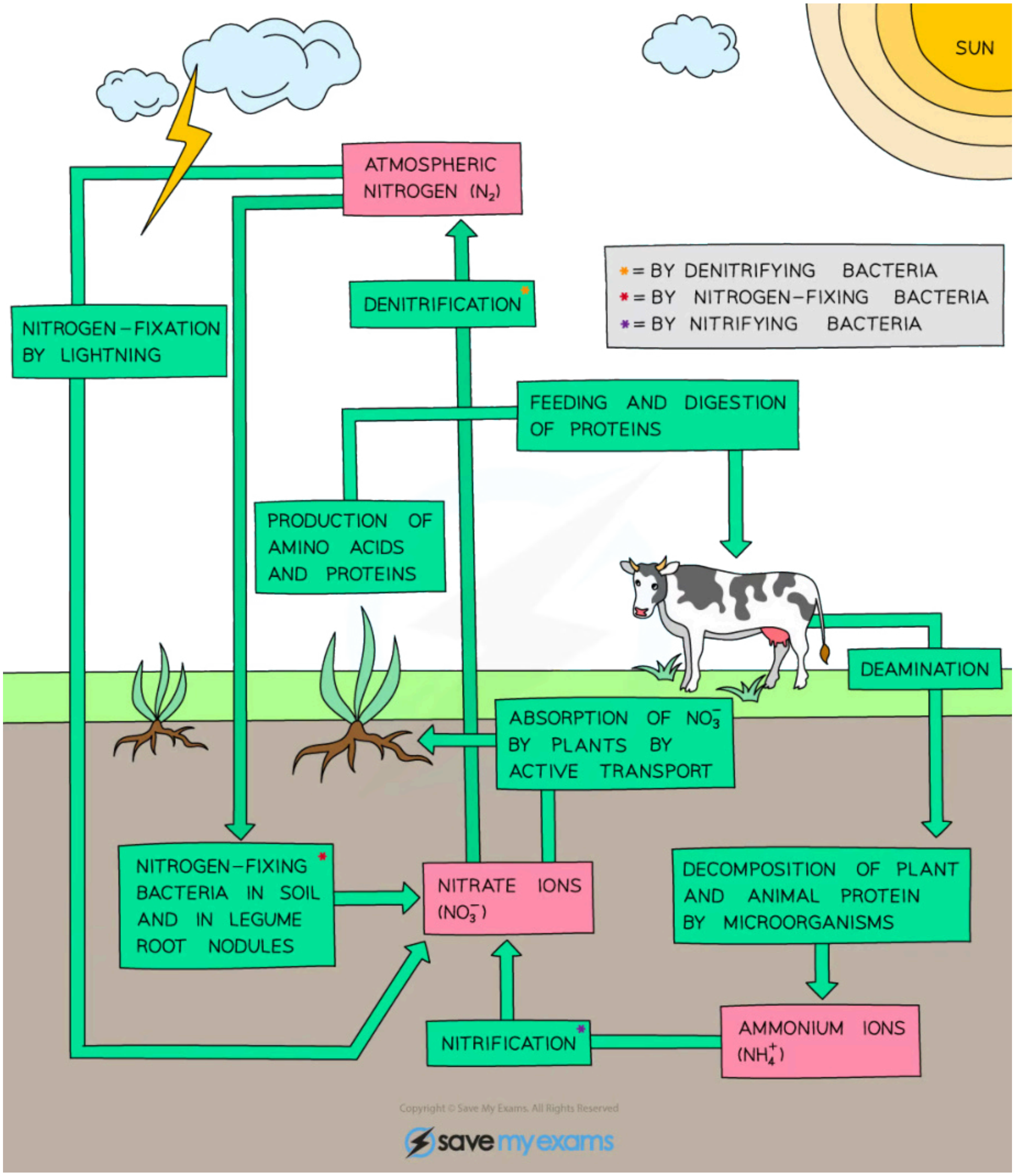
Nitrogen Cycle

- The nitrogen cycle is the process through which nitrogen moves between **organic** and **inorganic forms** in ecosystems
  - **Organic nitrogen** is found in proteins, DNA, and other compounds in living organisms and in dead organic matter
    - After death, organic matter decomposes, returning nitrogen to the soil
  - **Inorganic nitrogen** exists in the atmosphere (as **nitrogen gas**, N_2), and as nitrogen compounds like **ammonia** (NH_3), **nitrites** (NO_2^-), and **nitrates** (NO_3^-) in soils and water
    - The atmosphere holds the largest store of nitrogen, mostly as N_2 gas, which makes up 78% of the air

The role of bacteria in the nitrogen cycle

- Bacteria are essential for converting nitrogen into usable forms:
  - **Nitrogen fixation**: bacteria (such as rhizobium) convert atmospheric nitrogen (N_2) into ammonia (NH_3), which plants can use
    - This can happen in the soil or through symbiotic relationships with plants like legumes
  - **Nitrification**: nitrifying bacteria convert ammonia (NH_3) into nitrites (NO_2^-), then into nitrates (NO_3^-)
    - Plants absorb these nitrates through their roots
  - **Denitrification**: denitrifying bacteria convert nitrates (NO_3^-) back into nitrogen gas (N_2)
    - This nitrogen gas then returns to the atmosphere
    - This process happens in **anaerobic (low oxygen) conditions**, like waterlogged soils
  - **Decomposition (ammonification)**: when plants and animals die, decomposing bacteria break down their nitrogenous compounds into ammonium (NH_4^+)

Your notes



Nitrogen cycle systems diagram

Denitrification in anaerobic conditions

- Anaerobic conditions (low oxygen) occur in waterlogged soils

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- This is where denitrification takes place
  - Denitrification reduces nitrogen availability for plants by converting nitrates into nitrogen gas
  - Plants in these areas grow poorly because they can't absorb enough nitrogen, which is essential for growth
  - Some insectivorous plants, like **pitcher plants** and **sundews**, have adapted to these environments by obtaining nitrogen from insects instead

Mutualistic relationships and nitrogen fixation

- Plants cannot use **atmospheric nitrogen** directly
- However, **some plants**, such as **legumes** (like peas, beans, and clover), form mutualistic relationships with nitrogen-fixing bacteria
  - These bacteria live in **root nodules** of the plants and convert nitrogen gas into ammonia
  - This gives these plants a competitive advantage in nitrogen-poor soils
    - This is because they can now access nitrogen from the atmosphere, unlike other plants

Nitrogen flows: transfers and transformations

- **Transfer processes** (movement of nitrogen without changing its form):
  - **Mineral uptake**: plants absorb nitrates (NO_3^-) from the soil
  - **Consumption**: animals eat plants or other animals, taking in nitrogen in the form of proteins and moving nitrogen through the food chain
  - **Excretion**: animals release nitrogen back into the environment through waste products (urea, ammonia, faeces)
  - **Death and decomposition**: dead plants and animals add nitrogen back into the soil when they decompose
- **Transformation processes** (nitrogen changes form):
  - **Nitrogen fixation**: Nitrogen gas (N_2) → Ammonia (NH_3)
  - **Nitrification**: Ammonia (NH_3) → Nitrites (NO_2^-) → Nitrates (NO_3^-)
  - **Ammonification**: Organic nitrogen (proteins) → Ammonium (NH_4^+)
  - **Denitrification**: Nitrates (NO_3^-) → Nitrogen gas (N_2)
- Nitrogen fixation can also occur through **lightning**
  - The energy from lightning breaks nitrogen molecules (N_2) in the atmosphere

- This allows nitrogen atoms to combine with oxygen to form nitrogen oxides (NO and NO_2)
- These nitrogen oxides dissolve in rain and fall to the ground as nitrates (NO_3^-), a usable form of nitrogen for plants

Your notes

Human Impacts on the Nitrogen Cycle (HL)

Your notes

Human Impacts on the Nitrogen Cycle

Human activities altering the nitrogen cycle

Deforestation

- Removing forests reduces the amount of **vegetation** that can **absorb nitrogen from the soil** (for plant growth)
- This leads to an increase in nitrogen leaching into water bodies, where it can cause pollution
  - For example, deforestation in the Amazon has increased nitrogen runoff into rivers due to **exposed soil** and **soil erosion**
  - This has led to **eutrophication** (nutrient over-enrichment) and **harmful algal blooms**
  - These blooms deplete oxygen levels in the water, creating hypoxic or **dead zones** where aquatic life cannot survive
  - Studies have shown that deforestation in the Amazon basin has increased nitrogen concentrations in the rivers by 20–50%
    - Disrupting these freshwater ecosystems
    - Contributing to biodiversity loss

Agriculture

- The heavy use of **nitrogen-based fertilisers** on agricultural land to **increase crop growth** leads to excess nitrate being washed into rivers and oceans
- This contributes to eutrophication and causes dead zones in surrounding aquatic environments
  - For example, excessive fertiliser runoff in the Mississippi River basin causes a very large dead zone in the Gulf of Mexico every year

Aquaculture

- Fish farms often use large quantities of **feed** that introduce **excess nitrogen** into water systems
- Uneaten feed and fish waste add **nitrates** and **ammonia** to the water, causing algal blooms and oxygen depletion
  - For example, salmon farming in Norway contributes to nitrogen pollution in coastal waters

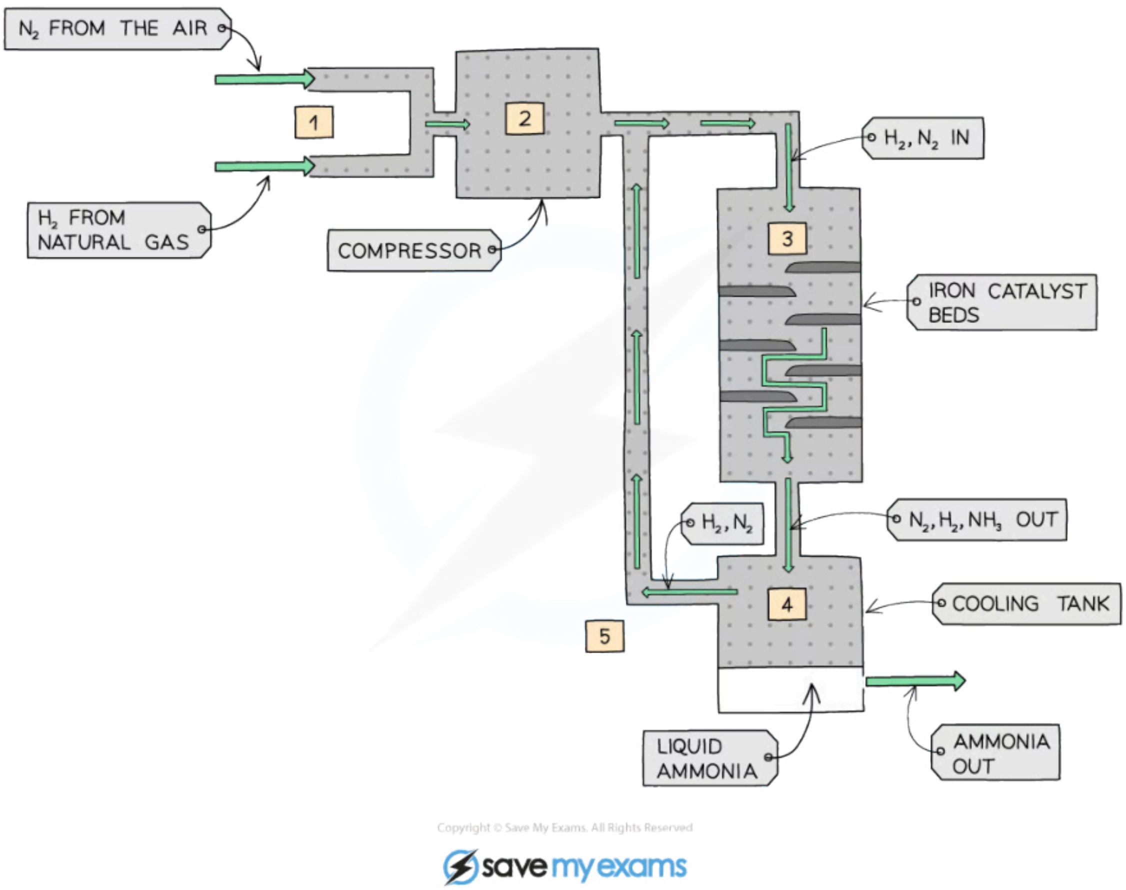
Urbanisation

- Cities and towns contribute to nitrogen pollution through:
  - **Sewage**:
    - Wastewater contains nitrogen from human waste, detergents, and food, which can enter rivers and oceans, increasing nitrogen levels
  - **Stormwater runoff**:
    - Rainwater picks up nitrogen from fertilisers, pet waste, and other pollutants on roads and carries it into water bodies
  - **Vehicle emissions**:
    - Cars release nitrogen oxides (NOx) into the air, which can contribute to nitrogen pollution when it settles onto land or water
    - These emissions can also react with water vapour to form nitric acid, leading to acid rain

The Haber process and its impact

- **The Haber process** is an industrial method for synthesising **ammonia** (NH_3) from **nitrogen** (N_2) in the atmosphere and **hydrogen** (H_2)
  - This ammonia can be used to produce fertilisers that enhance crop yields
- **Advantages**:
  - **Increases global food production** by improving crop yields
  - Provides a **reliable** and **large-scale** source of **nitrogen fertiliser** for agriculture
- **Disadvantages**:
  - Excess nitrogen from fertilisers contributes to pollution and environmental issues like **eutrophication** and **reduced biodiversity** in aquatic ecosystems
  - The Haber process requires **large amounts of energy**, typically from **fossil fuels**, contributing to greenhouse gas emissions

Your notes

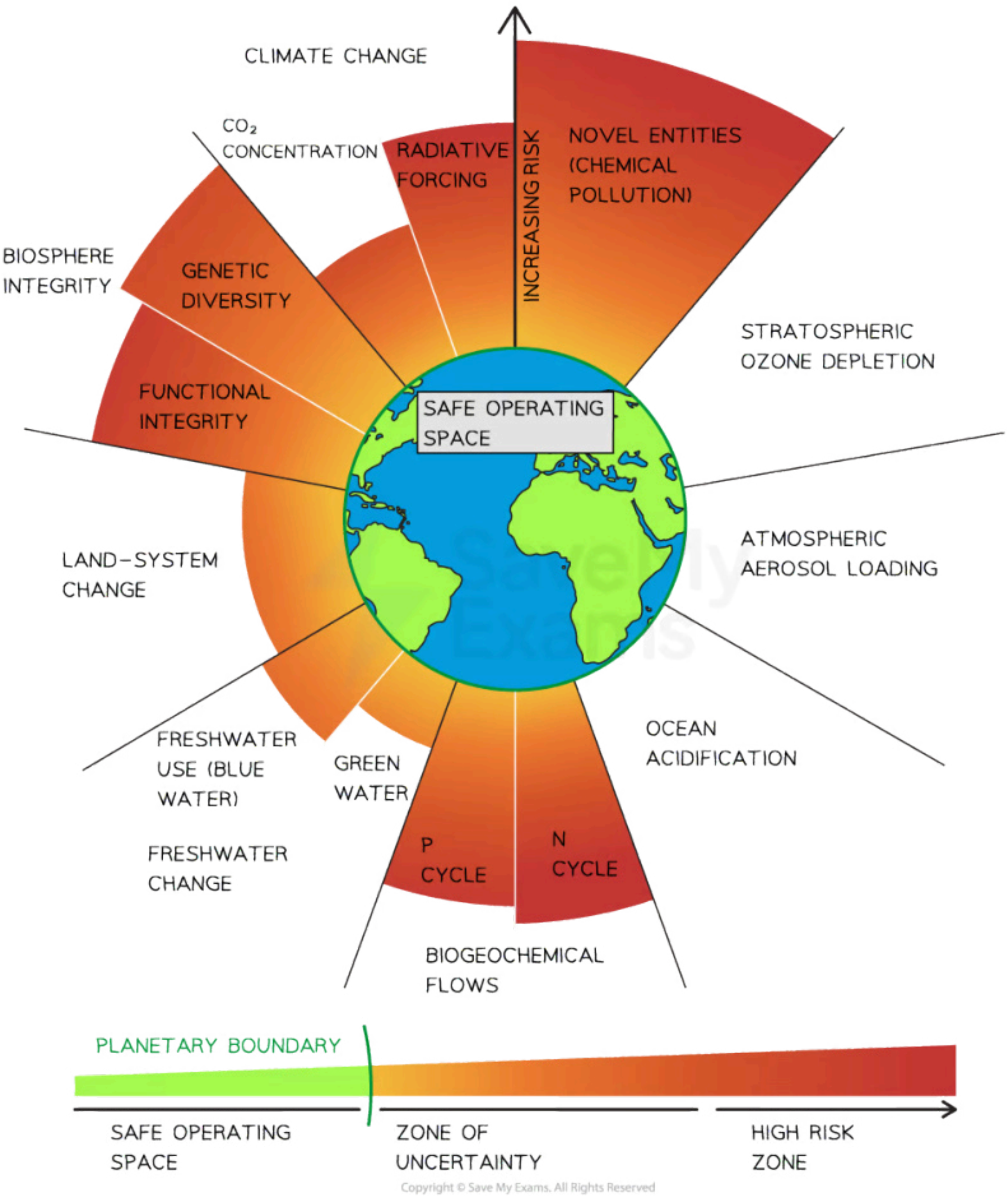


The production of ammonia by the Haber process

Crossing the nitrogen planetary boundary

- Nitrogen is one of the boundaries used in the planetary boundaries model
  - The planetary boundaries model outlines nine critical processes and systems that regulate the stability and resilience of our Earth system
- Human activities, especially the extensive use of nitrogen fertilisers, have resulted in excessive nitrogen in ecosystems
- This has pushed the nitrogen cycle **beyond its safe limits**, leading to potentially irreversible changes in the environment
  - Excess nitrogen disrupts natural cycles, causing water pollution and loss of biodiversity
  - Evidence shows that the nitrogen cycle is **beyond its safe operating space**

Your notes



Planetary Boundaries Model

Global collaboration to restore balance

- **Global dependence on fertilisers**:
  - Most of the world's food production relies on inorganic nitrogen fertilisers
  - This has created an unsustainable cycle of nitrogen pollution

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        - Global fertiliser use continues to increase, especially in rapidly industrialising countries like China and India
- **Collaborative solutions**:
    - To address the nitrogen crisis, countries must cooperate to:
        - Reduce nitrogen emissions
        - Improve nitrogen use efficiency in agriculture
- **Measures to restore balance**:
    - Use more sustainable farming techniques, such as **crop rotation** and **precision farming,** to reduce fertiliser use
    - Improve sewage treatment plants to reduce nitrogen pollution from urban areas
    - A key way to combat nitrogen pollution is to transition away from cars that emit nitrogen-based pollutants, such as those that run on petrol and diesel
        - For instance, EVs reduce emissions that contribute to nitrogen pollution and acid rain

Examiner Tips and Tricks

You don't need to know the specific chemical reactions or steps used in the Haber process for your exams. Just make sure you can recall its advantages and environmental disadvantages.